(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 520 519 A1

(12) EUROPEAN PATENT APPLICATION

(21) Application number: 92111017.7

(51) Int. Cl.5 H01J 37/32, H05H 1/46

(22) Date of filing: 29.06.92

(30) Priority: 27.06.91 US 722340
24.01.92 US 824856

(43) Date of publication of application:
30.12.92 Bulletin 92/53

(84) Designated Contracting States:
DE FR GB IT NL

(71) Applicant: APPLIED MATERIALS, INC.
3050 Bowers Avenue
Santa Clara California 95054-3299(US)

(72) Inventor: Collins, Kenneth S.
871 N. 19th St.
San Jose, CA 95112(US)
Inventor: Roderick, Craig A.
776 Pineview Dr.
San Jose, CA 95117(US)
Inventor: Trow, John R.
162 Knightshaven Way
San Jose, CA 95111(US)
Inventor: Yang, Chan-Lon
16788 Leroy Avenue
Los Gatos, CA 95032(US)
Inventor: Wong, Jerry Yuen-Kui
44994 Cougar Circle
Fremont, CA 94539(US)
Inventor: Marks, Jeffrey
4730 Cielo Vista Way
San Jose, CA 95129(US)
Inventor: Keswick, Peter R.
6371-A Joaquin Murieta Avenue
Newark, CA 94560(US)
Inventor: Groechel, David W.
27985 Via Ventana
Los Altos Hills, CA 94022(US)
Inventor: Pinson II, Jay D.
6879 Queenswood Way
San Jose, CA 95120(US)
Inventor: Ishikawa, Tetsuya
3-14-24 Kosaku
Funabashi City, Chiba 273(JP)
Inventor: Lei, Lawrence Chung-Lai
10236 Lockwood Dr.
Cupertino, CA 95014(US)
Inventor: Toshima, Masato M.
1614 Swallow Dr.
Sunnyvale, CA 94087(US)

(74) Representative: DIEHL GLAESER HILTL & PARTNER
Patentanwälte Flüggenstrasse 13
W-8000 München 19(DE)

(54) Plasma processing reactor and process for plasma etching.

(57) A domed plasma reactor chamber (10) uses a device such as an antenna (30) driven by RF energy (LF, MF, or VHF) which is electromagnetically coupled inside the reactor dome (17). The antenna (30) generates a high density, low energy plasma inside the chamber (16) for etching metals, dielectrics and semiconductor materials. Auxiliary RF bias energy applied to the wafer support cathode (32C) controls the cathode sheath voltage and controls the ion energy independent of density. Various magnetic and voltage processing enhancement techniques are disclosed, along with etch processes, deposition processes and combined etch/deposition processes. This allows processing of sensitive devices (5) without damage and without microloading, thus providing high yields.

EP 0 520 519 A1

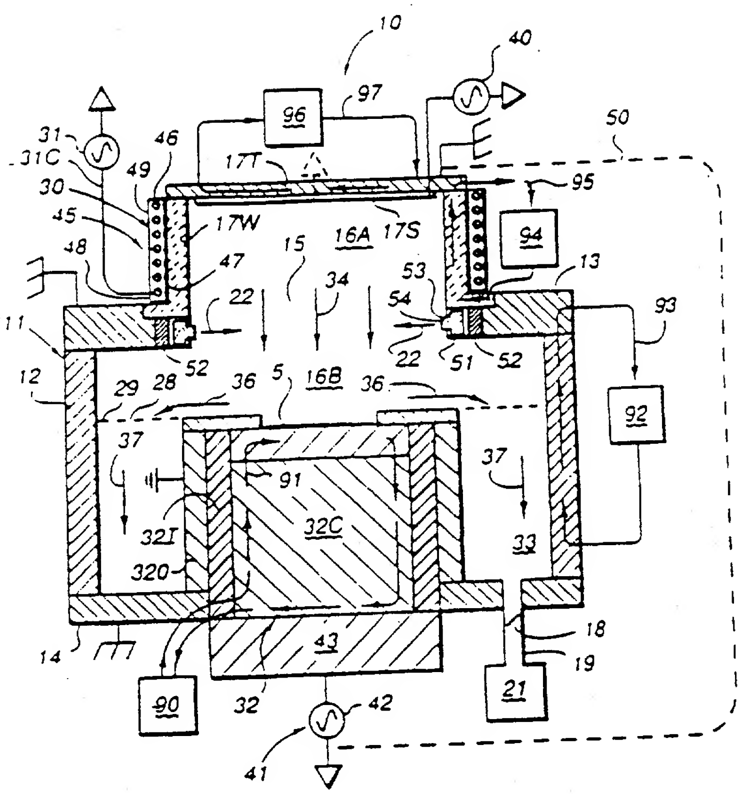
10
40
97
96
50
31
31C
30
45
46
49
17T
95
17W
16A
17S
94
15
48
47
34
53
13
22
54
93
11
12
52
22
51
52
29
28
36
5
16B
36
92
37
37
91
32C
33
32I
320
18
14
43
19
90
32
42
21
41

Figure 1

1. FIELD OF THE INVENTION

The present invention relates to RF plasma processing reactors or apparatuses and a process for plasma etching.

2. DESCRIPTION OF THE RELATED TECHNOLOGY

The trend toward increasingly dense integrated geometries has resulted in components and devices of very small geometry which are electrically sensitive and susceptible to damage when subjected to wafer sheath voltages as small as approximately 200-300 volts due to energetic particle bombardment or radiation. Unfortunately, such voltages are of smaller magnitude than the voltages to which the circuit components are subjected during standard integrated circuit fabrication processes.

Structures such as MOS capacitors and transistors fabricated for advanced devices have very thin (thickness < 200 Angstroms) gate oxides. These devices may be damaged by charge-up, resulting in gate breakdown. This can occur in a plasma process when neutralization of surface charge does not occur, by non-uniform plasma potential/or density, or by large RF displacement currents. Conductors such as interconnect lines may be damaged for similar reasons as well.

RF Systems

Consider first prior art semiconductor processing systems such as CVD (chemical vapor deposition) and RIE (reactive ion etching) reactor systems. These systems may use radio frequency energy at low frequencies from about 10-500 KHz up to higher frequencies of about 13.56-40.68 MHz. Below about 1 MHz, ions and electrons can be accelerated by the oscillating electric field, and by any steady state electric field developed in the plasma. At such relatively low frequencies, the electrode sheath voltage produced at the wafers typically is up to one or more kilovolts peaks, which is much higher than the damage threshold of 200-300 volts. Above several MHz, electrons are still able to follow the changing electric field. More massive ions are not able to follow the changing field, but are accelerated by steady state electric fields. In this frequency range (and at practical gas pressures and power levels), steady state sheath voltages are in the range of several hundred volts to 1,000 volts or more.

Magnetic Field-Enhancement

A favorite approach for decreasing the bias voltage in RF systems involves applying a magnetic field to the plasma. This B field confines the electrons to the region near the surface of the wafer and increases the ion flux density and ion current and, thus, reduces the voltage and ion energy requirements. By way of comparison, an exemplary non-magnetic RIE process for etching silicon dioxide might use RE energy applied at 13.56 MHz, an asymmetrical system of 10-15 liters volume, 6.65×10^{-5} bar (50 millitorr) pressure and an anode area to wafer-support cathode area ratio of approximately (8-10) to 1, and develop wafer (cathode) sheath voltage of approximately 800 volts. The application of a magnetic field of 6×10^{-3}T (60 gauss) may decrease the bias voltage approximately 25-30 percent, from 800 volts to about 500-600 volts, while increasing the etch rate by as much as about 50 percent.

However, the application of a stationary B field parallel to the wafer develops an E x B ion/electron drift and an associated plasma density gradient which is directed diametrically across the wafer. The plasma gradient causes non-uniform etching, deposition and other film properties across the wafer. The non-uniformities may be decreased by rotating the magnetic field around the wafer, typically either by mechanical movement of permanent magnets, or by using pairs of electromagnetic coils which are driven in quadrature, 90 degrees out of phase, or by instantaneously controlling the current in pairs of coils to step or otherwise move the magnetic field at a controlled rate. However, although rotating the field reduces the non-uniformity gradient, typically some degree of non-uniformity remains.

Furthermore, it is difficult to pack coils and, in particular, to pack two or more pairs of coils about a chamber and to achieve a compact system, especially when using a Helmholtz coil configuration and/or a multi-chamber system of individual magnetic-enhanced reactor chambers surrounding a common loadlock.

A unique reactor system which has the capability to instantaneously and selectively alter the magnetic field strength and direction, and which is designed for use in compact multi-chamber reactor systems, is disclosed in commonly assigned U.S. Patent 4,842,683, issued June 27, 1989, in the name of inventors Cheng et al.

Microwave/ECR Systems

Microwave and microwave ECR (electroncylotron resonance) systems use microwave energy of frequencies >800 MHz and, typically, frequencies of 2.45 GHz to excite the plasma. This technique produces a high density plasma, but low particle energies which may be below the minimum reaction threshold energy for many processes, such as the reactive ion etching of silicon dioxide. To compensate, energy-enhancing low frequency electrical power is coupled to the wafer support electrode and through the wafer to the plasma. Thus, the probability of wafer damage is decreased relative to previous systems.

Microwave and microwave ECR systems operated at practical power levels for semiconductor wafer processing such as etch or CVD require large waveguide for power transmission, and expensive tuners, directional couplers, circulators, and dummy loads for operation. Additionally, to satisfy the ECR condition for microwave ECR systems operated at the commercially available 2.45 GHz, a magnetic field of 875 gauss is necessitated, requiring large electromagnets, large power and cooling requirements.

Microwave and microwave ECR systems are not readily scalable. Hardware is available for 2.45 GHz because this frequency is used for microwave ovens. 915 MHz systems are also available, although at higher cost. Hardware is not readily or economically available for other frequencies. As a consequence, to scale a 5-6 in. microwave system upward to accommodate larger semi-conductor wafers requires the use of higher modes of operation. This scaling at a fixed frequency by operating at higher modes requires very tight process control to avoid so-called mode flipping to higher or lower order loads and resulting process changes. Alternatively, scaling can be accomplished, for example, for a 5-6 in. microwave cavity, by using a diverging magnetic field to spread out the plasma flux over a larger area. This method reduces effective power density and thus plasma density.

HF Transmission Line System

European patent applications 91112905.4 and 91112917.5 are incorporated by reference. In these references are disclosed a high frequency VHF/UHF reactor system in which the reactor chamber itself is configured in part as a transmission line structure for applying high frequency plasma generating energy to the chamber from a matching a network. The unique integral transmission line structure permits satisfaction of the requirements of a very short transmission line between the matching network and the load and permits the use of relatively high frequencies, 50 to 800 MHz. It enables the efficient, controllable application of RE plasma generating energy to the plasma electrodes for generating commercially acceptable etch and deposition rates at relatively low ion energies and low sheath voltages. The relatively low voltages reduce the probability of damage to electrically sensitive small geometry semiconductor devices. The VHF/UHF system avoids various other prior art shortcomings, such as the above-described scalability and power limitations.

An object of the present invention is to propose further improved RF plasma processing systems. This object is solved by the RF plasma process apparatuses of any one of the independent claims 1, 2, 3, 4, 5, 6, 9 and 11 and the process of independent claim 20. Further advantageous features, aspects and details of the invention are evident from the dependent claims, the description, examples and the drawings. The claims are intended to be understood as a first non-limiting approach of defining the invention in general terms.

The invention provides plasma reactor which uses a radio frequency (RF) energy source and a multiple coil antenna for inductively coupling the associated RF electromagnetic wave to the plasma.

In one aspect, the invention which overcomes prior art shortcomings is embodied in the construction and operation of an RF plasma processing system comprising a vacuum chamber having a source region and a processing region; means for inductively coupling RE electromagnetic energy into the processing chamber for generating a plasma within the chamber to fabricate an article such as a semiconductor wafer positioned, for example, at the coupling means or downstream relative to the coupling means; and a triode arrangement comprising an RF cathode in the processing region, an anode defined by the chamber walls, and a source region electrode which is electrically floating, grounded or connected to RF bias, for enhancing plasma processing. The construction of the source region electrode and/or the chamber walls defining the source region may include silicon for enhancing processes such as oxide etching.

Preferably, LF/VHF (low frequency to very high frequency) RF power within the range 100 KHz to 100 MHz is used. More preferably, LF/HF power within the range 100 KHz to 10 MHz is used. Most preferably, MF (medium frequency) power is used within the range 300 KHz to 3 MHz. Preferably, the coupling means is a multiple turn, cylindrical coil antenna of uncoiled electrical length < $\lambda/4$ where λ is the wavelength of the high frequency RF excitation energy applied to the coil antenna during plasma operation.

The invention also provides means connected to the antenna for tuning the antenna to resonance as well as load means connected to the antenna to match the input impedance of the source to the output impedance of the means for supplying RF energy for the antenna. The tuning means may be a variable capacitance electrically connected between one end of the antenna and RF ground. The load means may be a variable capacitance electrically connected between the other end of the antenna coil and RF ground. RF energy may be applied via a tap at a selected location along the coil antenna.

In another aspect, the system includes a dielectric dome or cylinder which defines the source region. Preferably, the coil antenna surrounds the dome for inductively coupling the high frequency electromagnetic energy into the chamber. The article which is fabricated can be located within the source region or dome, within or closely adjacent the volume or the bottom turn of the antenna, or preferably, downstream of the antenna.

The invention also provides means for supplying gas to the chamber which comprises a gas inlet at the top of the dome, a first ring manifold at the base of the dome source region, and a second ring manifold surrounding at the wafer support electrode, for selectively supplying processing diluent, passivation and other gases to the chamber.

In yet another aspect, an AC power supply and control system capacitively couples AC bias power typically of the same or similar frequency as the source coil power, to a wafer support cathode, thereby effecting control of the cathode sheath voltage and ion energy, independent of the plasma density control effected by the source radio frequency power. The system provides bias frequency selected to achieve a number of objectives. First, the upper frequency limit is selected to prevent "current-induced" damage (a too high frequency can cause charge-up damage to sensitive devices.) The lower frequency limit is selected in part to preclude "voltage-induced" damage. Lower frequency bias also yields higher wafer sheath voltages per unit bias power (less heating of substrates) and contributes less to plasma density and thus affords better independent control of ion density and energy. However, a too low bias frequency allows ions to follow the RF component of the wafer sheath electric field, thereby modulating ion energies. The result is a higher peak-to-average energy ratio and wider (double peak) ion energy distribution. Very low bias frequency causes insulator charge-up, inhibiting ion-induced processes during part of the bias frequency period. Conveniently, the preferred frequency ranges for satisfying the above considerations correspond to the source frequency ranges. That is, preferably LF/VHF (low frequency to very high frequency) power within the range 100 KHz to 100 MHz is used. More preferably, LF/HF power within the range 100 KHz to 10 MHz is used. Most preferably, MF (medium frequency) power is used within the range 300 KHz to 3 MHz.

The invention further provides control means for cyclically pulsing the DC bias voltage between low and high values selected, respectively, to form a passivation coating on a first selected material on the wafer for providing a relatively low etch rate of that material and for selectively etching a second selected material at a relatively high rate and selectivity.

In another aspect, the chamber is evacuated by a first vacuum pump means connected to the chamber proper and a second vacuum pump means connected to the dome for establishing a vertical pressure differential across the dome for establishing a flow of neutral particles out of the dome, and wherein the voltage at the wafer support electrode is sufficient to overcome the pressure differential so that charged particles flow toward the chamber proper.

Other aspects include a conductive, Faraday shield of different configurations which is interposed between the coil antenna or other coupling means and the chamber to prevent coupling of the electric field component of the high frequency electromagnetic energy into the chamber. Also, a high frequency reflector positioned surrounding the coil or other coupling means concentrates radiation of the high frequency energy into the chamber.

Magnetic enhancement is supplied by peripheral permanent or electromagnet arrangements which apply a controlled static magnetic field parallel to the axis of the antenna, selected from uniform, diverging and magnetic mirror configurations, for controlling the location of and the transport of the plasma downstream relative to the wafer. Also, magnets may be mounted around the source and/or the chamber for applying a multipolar cusp field to the chamber in the vicinity of the wafer for confining the plasma to the wafer region while substantially eliminating the magnetic field across the wafer. In addition, a magnetic shunt may be positioned surrounding the wafer and the wafer support electrode for diverting any magnetic field from the wafer support electrode.

The system construction permits scaling of its size by selecting the frequency of operation, while retaining low mode operation.

In other, process aspects, the invention is embodied in a process for generating a plasma, comprising providing a vacuum chamber having source and process regions; supporting an article on an electrode in

the process region; supplying processing gas to the chamber; using a cylindrical coil antenna of more than one coil turn having an electrical length < λ/4 wherein λ is the wavelength of RF energy applied to the antenna, inductively coupling RF energy into the source region for generating a plasma to fabricate one or more materials on the article; and capacitively coupling RF energy into the chamber via the support electrode for controlling sheath voltage at the support electrode.

The process also may encompass automatically and iteratively tuning the antenna to resonance and loading the input impedance thereof to the impedance of the RF energy supply for the antenna.

In another aspect, the process for generating a plasma comprises providing a vacuum chamber having source and process regions, and having walls, an electrode in the process region and an electrode in the source region; connecting the electrode in the process region, the walls of the chamber and the source electrode electrically, with the process region electrode being the cathode, the walls being the anode and the electrical connection of the source electrode being selected from ground, floating and RF or DC bias, supporting an article on the electrode in the process region; supplying processing gas to the chamber using a cylindrical coil antenna of one or more coil turns and having an electrical length < λ/4 where λ is the wavelength of RF energy applied to the antenna, inductively coupling RF energy into the source region for generating a plasma to fabricate one or more materials on the article; and capacitively coupling RF energy into the chamber via the support electrode for controlling sheath voltage at the support electrode

At least one of the source electrode and the chamber wall in the source region may be or contain silicon and the source electrode may be RF biased, for freeing the silicon into the plasma to enhance the processing.

In another aspect, the antenna power and the bias power delivered to the electrode are controlled for selectively effecting anisotropic, semi-anisotropic and isotropic etching.

An aspect of the process encompasses etching silicon oxide in the presence of silicon, the use of silicon enhancement, and/or the use of additives such as CO and CO_2 for selectivity and etch profile enhancement. The process encompasses cyclically driving the bias voltage to a low value selected to form an etch suppressing layer on the silicon and to a high value to etch the silicon oxide at a high rate relative to the silicon.

The process according to a further aspect also provides sputter deposition of silicon oxide and the process of, first, applying relatively low level RF power to the support electrode for depositing silicon oxide and, second, applying relatively high level RF power to the support electrode for net sputter facet depositing silicon oxide and planarizing the silicon oxide.

Specific process aspects include but are not limited to etching oxide, including etching contact holes in oxide formed over polysilicon (polycrystalline silicon) and etching via holes in oxide formed over aluminum; so-called "light" etching of silicon oxide and polysilicon; high rate isotropic and anisotropic oxide etching; etching polysilicon conductors such as gates; photoresist stripping; anisotropic etching of single crystal silicon; anisotropic photoresist etching; low pressure plasma deposition of nitride and oxynitride; high pressure isotropic conformal deposition of oxide, oxynitride and nitride; etching metals, such as aluminum and titanium, and compounds and alloys thereof; and sputter facet deposition, locally and globally, and with planarization.

Brief Description of the Drawings

FIGURES 1-3 are simplified sectional views of a plasma reactor chamber in accordance with the invention;

FIGS. 4-9 are schematic diagrams of tuning circuits for matching the impedance of a power generator with the impedance of a plasma load;

FIG. 10 is a graph showing how etch rates for silicon and silicon dioxide vary with increasing dc bias voltage in a plasma etching process;

FIG. 11 is a graph showing the waveform of a dc bias voltage in accordance with one aspect of the invention, wherein the bias voltage is periodically pulsed from a high base line value to a much lower value;

FIG. 12 is a graph showing the waveform of a dc bias voltage in accordance with another aspect of the invention, wherein the bias voltage is varied about an average value at a first frequency, and the amplitudes of the excursions of bias voltage are varied in accordance with a second frequency, lower than the first;

FIG. 13 is a diagrammatic view of the plasma processing chamber, showing an arrangement of magnets for enhancement of plasma density an uniformity;

FIGS. 14A-14D are diagrams showing how an axial magnetic field may be shaped with respect to a wafer

being processed, to enhance processing; and

FIGS. 15A and 15B are fragmentary diagrams depicting two alternative Faraday shield structures for reducing a steady state electrostatic field coupling to the plasma in the chamber; and

FIG. 16 is block diagram of an illustrative system for controlling the various components of plasma reactor of the invention.

Detailed Description of the Preferred Embodiment(s)

1. OVERVIEW

FIGS. 1-3 are schematic sectional views of a plasma reactor chamber system 10 for processing a semiconductor wafer 5 which uses an inductive plasma source arrangement, a magnetically-enhanced plasma source arrangement, a capacitively coupled bias arrangement and other aspects of the present invention. The three figures illustrate preferred and alternative features of the system; three figures are used because of drawing space limitations. The exemplary chamber is a modification of that depicted in the above-mentioned co-pending incorporated patent applications, which include an integral transmission line structure. The salient features of the invention are applicable generally to plasma reactor chambers. Furthermore, it will be understood by those of skill in the art and from the description below that various features of the invention which cooperatively enhance the performance of the reactor system may be used separately or may be selectively omitted from the system. For example, the process conditions provided by the inductive plasma source arrangement and capacitively coupled bias source arrangement frequently eliminate any need for magnetic enhancement.

The exemplary system 10 includes a vacuum chamber housing 11, formed of anodized aluminum or other suitable material, having sidewalls 12 and top and bottom walls 13 and 14. Anodized aluminum is preferred because it suppresses arcing and sputtering. However, other materials such as bare aluminum with or without a process-compatible liner of polymer or quartz or ceramic can be used. Top wall 13 has a central opening 15 between a lower chamber wafer processing section 16B defined between walls 12-12 and an upper chamber source section 16A defined by a dome 17. The dome may be configured as an inverted single- or double-walled cup which is formed of dielectric material such as, preferably, quartz or several other dielectric materials, including alumina and alpha-alumina (sapphire). In the preferred arrangement shown in FIG. 1, the dome 17 comprises a cylindrical wall 17W of dielectric such as quartz and a cover or top 17T typically of aluminum or anodized aluminum. For processes such as high selectivity oxide etching, a silicon or silicon-containing top wall means, and silicon covered dome sidewalls are preferred.

As shown in FIG. 1, the evacuation of the interior of the chamber housing 11 (chamber 16) is controlled by a throttle valve 18 (which regulates pressure independent of flow rate) in a vacuum line 19 which is connected to the bottom wall 14 and connects to a vacuum pumping system 21 comprising one or more vacuum pumps.

As described in Section 10, the chamber components, including the chamber walls and dome, can be heated and/or cooled for process performance. For example, the dome can be heated or cooled by a liquid or gas heat transfer medium, or heating elements can be used to heat the dome directly.

As described in Section 2 and depicted in FIG. 2, process gases, purge gases, diluents, etc., can be supplied to the chamber by three manifold injection sources, G1, G2, G3, located, respectively, at the base of the source (dome), the top plate 17T of the source, and peripheral to the wafer. The gases are supplied to the chamber 11, for example, typically from one or more sources of pressurized gas via a computer-controlled flow controller (not shown). At the main gas inlet manifold G1, the gases enter the internal vacuum processing chamber 16, as indicated at 22, through a quartz ring 51 gas manifold 52, which is mounted on the inside of or integral with, top wall 13. The manifold 52 preferably supplies etching gas and/or deposition gas at a slight upward angle to the chambers/chamber sections 16B and 16A for developing an etching and/or deposition plasma upon application of RF energy. A top manifold arrangement G2 in the top plate 17T of the dome 17 may be used to inlet reactant and other gases into the chamber 16. Also, a manifold arrangement G3 may be provided which is peripheral to the wafer to supply reactant and other gases.

RF energy is supplied to the dome by a source comprising an antenna 30 of at least one turn or coil which is powered by an RF supply and matching network 31. The antenna 30 preferably has a multiple turn cylindrical configuration. The coil 30 defines a minimum conductor electrical length at a given frequency and a given source (coil) diameter and preferably has an electrical length less than one-quarter wavelength ($<\lambda/4$) at the operating frequency. By itself, the antenna 30 is not a resonator but is tuned to resonance as described below in Section 5 for efficient inductive coupling with the plasma source by Faraday's law of

inductive coupling.

Preferably, the gas flow from the chamber source section 16A is downward toward the wafer 5 and is then pumped radially outward from the wafer. To this end, an annular vacuum manifold 33 may be defined about cathode transmission line structure 32, between chamber wall 12 on one side and the outer transmission line conductor 320 on the other, and between the chamber bottom wall 14 on the bottom and a conductive pumping screen 29 on the top. The manifold screen 29 is interposed between the vacuum manifold 33 and the wafer processing chamber 16B and provides a conductive electrical path between chamber walls 12 and the outer conductor 320 of the transmission line structure 32. The manifold 33 defines an annular pumping channel for implementing uniform radial pumping of exhaust gases from the periphery of wafer 5. The exhaust manifold 33 communicates into the exhaust gas system line 19. The gas flow is along paths 22 from manifold G1 into the dome/source and/or along path 24 from manifold G2 into the dome/source and/or along paths 26 from manifold G3 radially inward toward the wafer 5. The overall gas flow is along path 34 from the upper chamber source section 16A toward wafer 5, along path 36 from the wafer and through screen 29 into the gas outlet manifold 33, and along path 37 from the exhaust manifold 33 to the exhaust system 21. It should be noted that the conductive manifold screen 29 and the cathode transmission line structure are optional. Typically, at the low end of the frequencies of interest, the wavelength is very long and, thus, the transmission line structure is unnecessary.

This contrasts with conventional RF system arrangements, in which the RF power is applied between two electrodes, typically the wafer support electrode 32C, the upper surface of which supports wafer 5, and a second electrode which is the sidewalls 12, top wall 13 and/or manifold 23 of the reactor chamber.

Specifically, the antenna 30 is positioned outside and adjacent the dome 17 and the plasma chamber 16A for coupling the RF electromagnetic (em) energy into the source chamber 16A to induce electric fields in the process gas. By Faraday's Law of induction coupling, the changing B (magnetic) component of the em energy energizes the process gas and thus forms a plasma in chamber 16 (numeral 16 collectively designates the chamber 16A and 16B and the plasma) characterized by relatively high density and low energy ions. The plasma is generated in the dome 17 concentrated in the small volume defined within the coil antenna 30. Active species including ions, electrons, free radicals and excited neutrals move downstream toward the wafer by diffusion and by bulk flow due to the prevailing gas flow described herein. Also, as described in Section 7 an appropriate magnetic field can be used to extract ions and electrons toward the wafer as described below. Optionally, but preferably, a bias energy input arrangement 41, FIG. 1, comprising a source 42 and a bias matching network 43 couples RF energy to the wafer support electrode 32C for selectively increasing the plasma sheath voltage at the wafer and thus selectively increasing the ion energy at the wafer.

A reflector 45 which essentially is an open-bottom box encloses the antenna at the top and sides but not at the bottom. The reflector prevents radiation of the RF energy into free space and thereby concentrates the radiation and dissipation of the power in the plasma to enhance efficiency.

As described in detail in Section 7, a Faraday shield 45, FIG. 3, may be positioned just inside, above and below the antenna 30 to permit the magnetic field coupling to the plasma but preclude direct electric field coupling, which could induce gradients or non-uniformities in the plasma, or accelerate charged particles to high energies.

As described in Section 8, optionally, one or more electromagnets 76,76, FIG. 13, or permanent magnets are mounted adjacent the chamber enclosure 11 for providing a magnetic field for enhancing the density of the plasma at the wafer 5, for transporting ions to the wafer, or for enhancing plasma uniformity.

As is described fully in Section 4, the invention uses the magnetic component of inductively coupled electromagnetic energy, typically at frequencies much lower than microwave or microwave-ecr frequencies, to induce circular electric fields inside a vacuum chamber for generating a plasma characterized by high density and relatively low energy, without coupling potentially damaging high power RF energy through the wafer 5. In the preferred, illustrated downstream plasma source arrangement, the RF energy is fully absorbed remote from the wafer, with high plasma density, ensuring that the wave does not propagate to the wafer and thus minimizing the probability of damage. Selectively, and optionally, RF bias energy is applied to the wafer support electrode 32C for increasing the wafer sheath voltage and, thus, the ion energy, as required.

The chamber 11 is capable of processing semi-conductor wafers – deposition and/or etching – using total chamber pressures of about 1.33×10^{-7} bar to about 6.65×10^{-2} bar (about 0.1 mT to about 50 torr), and, for etching, typically 1.33×10^{-7} bar to 2.66×10^{-4} bar (0.1 mT to 200 mT). Our chamber can operate at pressures $<6.65 \times 10^{-6}$ bar (< 5 millitorr) and, in fact, has run successfully at 2.66×10^{-6} bar (2 millitorr). However, higher pressures are preferred for certain processes because of the increased pumping speed and higher flow rates. For example, for oxide etching a pressure range of about 6.65×10^{-6} bar to

about 6.65 x 10^{-5} bar (about 5mT (millitorr) to about 50 mT) is preferred.

Such relatively high pressures require close spacing between the source and the wafer. The chamber can operate successfully at very suitable, close spacing, d, between the wafer 5 and the bottom turn of the antenna 30 of about 5 centimeters/ 2 inches without charge-up damage to sensitive devices and, thus, is able to realize the advantages of such very close spacing: enhanced etch rates and selectivity; reduced bias voltage requirement and ion energy requirement for a given etch rate; and enhanced etch uniformity across the wafer. For example, reducing the spacing, d, between the wafer 5 and the source antenna 30 from 10 cm/4 in (which itself is close spacing) to 5 cm/2 in has reduced the voltage requirement by half and has increased the uniformity from about 2.5 percent to about 1 percent.

2. MULTIPLE GAS INJECTION

As mentioned, our chamber incorporates multiple gas injection sources G1, G2, G3, FIG. 2 for the purpose of injecting reaction, purge, etc., gases at different locations to enhance a particular process according to the requirements of that process (etching, deposition, etc.) and the particular material(s) used in that process. First, the chamber includes a standard radial gas distribution system G1 at the periphery of the base/bottom of the source region 16B. In a presently preferred configuration, the G1 injection system comprises a quartz gas distribution ring 51 at the bottom of the source and a peripheral annular manifold 52 defining a distribution channel which feeds gas to the ring. The ring has inward facing radial holes 53-53 and, preferably, stepped sintered ceramic porous gas diffuser plugs 54-54 inserted in the holes to prevent hollow cathode discharge.

The second gas injection arrangement, G2, comprises a grounded or floating or biased dome top plate 17T of material such as anodized aluminum having a center gas inlet hole 56 filled with a porous ceramic diffuser disk 57.

The third gas injection source, G3, comprises a ring-shaped gas inlet manifold 58 mounted at the periphery of the wafer 5 (or a gas inlet incorporated into the clamp ring (not shown) used to hold the wafer in position against the support pedestal).

Example: Etching Silicon Oxide Over Polysilicon Using Polymer-Enhanced Selectivity

As alluded to above, various types of gases selected from etchant and deposition species, passivation species, diluent gases, etc., can be supplied to the chamber via one or more of the sources G1 through G3, to satisfy the requirements of particular etch and deposition processes and materials. For example, the present inductive source antenna 30 provides a very high density plasma and is very effective in dissociating the gases in the dome source region 16A of the chamber. As a consequence, when a polymer-forming species is supplied to the dome via G1, or G2, the highly dissociated species may coat the interior of the dome at the expense of coating the polysilicon and/or may be so fully dissociated that it does not adhere to the polysilicon surface which is to be protectively coated. A solution is to inlet etchant species such as C_2F_6 or CF_4 into the source region 16A via G1 or G2 or via G1 and G2, and supply a polymer-forming species such as CH_3F or CHF_3 via inlet G3, to form a polymer preferentially on the poly without destructive dissociation.

Example: Etching Silicon Oxide Over Polysilicon Using Silicon-Containing Gas Chemistry

Because of the high dissociation of the gases in the source region, fluorine-containing gases (even those in which the fluorine is tied up with carbon) typically produce free fluorine which etches silicon and, thus, reduces the etch selectivity for oxide. When high selectivity is required, a silicon-containing additive gas can be injected to tie up the free fluorine and diminish its silicon etching. The etchant gas and the silicon-containing additive gas can be introduced separately via G1 and G2 or can be introduced as a mixture via G1 and/or G2. Suitable fluorine-consuming silicon-containing additive gases include silane (SiH_4), TEOS, diethylsilane and silicon tetrafluoride (SiF_4).

The fluorine-consuming and polymer-forming additive gases can be used together in the same process to jointly enhance etch selectivity.

Example: Silicon Oxide Deposition

Deposition rate is enhanced by supplying the oxygen-containing species and a diluent such as O_2 and Ar_2 via G1 and/or G2 and supplying a silicon-containing gas such as SiH_4, via G3.

3. DIFFERENTIAL PUMPING

FIG. 3 depicts an alternative vacuum pumping configuration. In addition to the vacuum pumping system 21 which is connected to or near the bottom of the chamber, a vacuum pump 39 is connected via line 38 to the source region 16A inside the dome 17. The flow rates of the pumping systems 39 and 21 are selected so they generate vertically across the source region 16B a pressure differential, ΔP_p, which (1) opposes the transport of uncharged particles from the source 16A to the wafer 5, yet (2) is of lesser magnitude than the force, F_b, exerted by the bias voltage on charged particles such as electrons and ions. As a consequence of ΔP_p, uncharged particles such as radicals do not reach the wafer 5, but rather flow predominantly out the top vacuum connection 38. As a consequence of $F_{bc} > \Delta P_p$, charged electrons and ions flow predominantly to the processing region. This approach is useful, obviously, where it is desired to selectively keep radicals but not ions out of the wafer processing region. That situation occurs, for example, (1) during etching which uses polymer-forming gas chemistry, but polymers are formed in the source region which adhere to the chamber sidewalls and/or do not adhere well to the desired wafer surface and/or (2) when fluorine radicals are formed in the source region.

4. RF POWER, TOP AND BIAS SOURCES

1) Top or Antenna Source

Referring to FIG. 1, preferably, the operating frequency of the RF power supply 31 for the top source 30 is selected to provide a dense plasma, to minimize damage to sensitive devices and to provide efficient inductive coupling of the RF power to the plasma. Specifically, the upper frequency of the operating range is limited to minimize "current-induced" damage. The lower limit of the operating frequency is selected for efficiency of RF power coupling to the plasma. Preferably, LF/VHF (low frequency to very high frequency) AC power within the range about 100 KHz to 100 MHz is used. More preferably, LF/HF (low frequency to high frequency) power within the range 100 KHz to 10 MHz is used. Most preferably, MF (medium frequency) power within the range 300 KHz to 3 MHz is used.

2). Bottom or Bias Source

The AC power supply 42 for the wafer support cathode 32C, capacitively couples RF power to the plasma, thereby effecting control of various factors including cathode sheath voltage and ion energy, which are controlled independent of the plasma density control effected by the high frequency power. The bias frequency is selected to achieve a number of objectives. First, the upper frequency limit is selected to prevent current-induced charge-up damage to sensitive devices. A lower frequency is selected in part to preclude voltage-induced damage. Lower frequency bias also yields higher wafer sheath voltages per unit bias power (less heating) of substrates and contributes less to plasma density and, thus, affords better independent control of ion density and energy. However, a too low bias frequency allows ions to follow the RF component of the wafer sheath electric field, thereby modulating ion energies. The result would be a higher peak-to-average energy ratio and wider (peak-to-peak) ion energy distribution. Very low bias frequency causes insulation charge-up, inhibiting ion-induced processes during part of the bias frequency control.

We have discovered that, conveniently, the above considerations can be satisfied using bias frequency ranges which correspond to the source frequency ranges. That is, preferably the bias power is within the range about 100 KHz to about 100 MHz (LF/VHF frequencies). More preferably, the frequency of the bias power is within the range about 100 KHz to about 10 MHZ (LF/HF frequency). Most preferably, the frequency of the bias power is within the range 300 KHz to 3 MHz (MF frequencies).

3). Combined Operation of Top and Bias Sources

A preferred feature of the invention is to automatically vary the bottom or bias power supplied by power supply 42 to maintain a constant cathode (wafer) sheath voltage. At low pressures (<500 mt) in a highly asymmetric system, the DC bias measured at the cathode 32C is a close approximation to the cathode sheath voltage. Bottom power can be automatically varied to maintain a constant DC bias. Bottom or bias power has very little effect on plasma density and ion current density. Top or antenna power has a very strong ffect on plasma density and on current density, but very small effect on cathode sheath voltage. Therefor , it is desired to use top power to define plasma and ion current densities, and bottom power to

define cathode sheath voltage.

Because the radio frequency of the source 31 driving the antenna 30 is nonetheless much lower than the frequencies used in microwave or microwave-ECR applications, the optional smaller magnets operated at lower DC current by less expensive power supplies can be used, with associated smaller heat loads. In addition, as is obvious from the above discussion, coaxial cable such as 31C can be used instead of wave guides. In addition, the plasma non-uniformities caused by the E x B electron drift in other magnetic-enhanced or assisted systems are absent here, because the applied magnetic fields (both the magnetic component of the HF field applied via the antenna 30 and any static magnetic field applied by magnets 81) are substantially parallel to the electric field at the cathode. Thus, there is no E x B drift in the system.

A magnetic shunt path formed with a high permeability material may be used to allow a B field in the source (upper chamber 16A) but not at the wafer.

Optionally, permanent or electromagnets may be placed in a multi-polar arrangement around the lower chamber 16B, typically in an alternating pole north-south-north-south ... north-south arrangement, to generate a multi-cusp magnetic mirror at the source and/or chamber walls. The magnets may be vertical bar magnets or preferably horizontal ring magnets, for example. Such magnets may be used to reduce electron losses to the walls, thus enhancing plasma density and uniformity, without subjecting the wafer to magnetic fields.

4) Combination and Synchronism of RF Sources

As indicated above, the preferred frequency of operation of the top or antenna RF source and the preferred frequency of operation of the bottom or bias RF source both fall conveniently into the same range. One optional configuration approach is to combine these two RF sources into one single source, instead of using two separate sources. More generally, the possibilities are to supply all three RF signals (including RF bias to the third or top electrode) from a single source, or to use one source for the antenna and bottom bias and a second source for the third electrode, or to use three separate sources. To the extent that separate sources are used, additional considerations are whether the separate RF signals should be equal in frequency and, if so, whether they should be locked in some desired phase relationship. Preliminary study indicates that the answers to these questions depend primarily on the selected frequencies of operation. If a single frequency can be conveniently chosen for two or three of the RF sources, and if the frequency is unlikely to be changed for different processes for which the system is used, then a single RF source is the logical choice. If different frequencies are needed for the sources, based on the considerations discussed in subparagraphs 1-3 above, or if the frequencies may need to be changed for use in different processes, then separate RF sources will be needed. In the case where there are separate sources and the same frequency is selected, phase locking is an issue. For example, the sources may be synchronized such that the phase angle between the RF voltage input to the antenna and the RF voltage input to the bottom or wafer electrode is maintained at a constant value that is chosen to optimize process repeatability. At higher frequencies, such as above about 10 MHz, operation appears to be independent of phase or frequency locking.

5. ANTENNA TUNE AND LOAD

1) Tuning

Typically, the antenna 30 is tuned to resonance by (1) varying the frequency of the generator 31 to resonate with the antenna; or (2) a separate resonating element, connected to the antenna for tuning to resonance. For example, this tuning element can be a variable inductance-to-ground or a variable capacitance-to-ground.

Please note, inductive and capacitive tuning decreases the resonant frequency. As a consequence, it is desirable to build the system to the highest desirable resonant frequency to accommodate the decrease in resonant frequency when using capacitance or inductance tuning variables.

Automatic tuning is preferred and may be executed by using an impedance phase/magnitude detector to drive the tune/load variables. See FIG. 16 and Section 9. Alternatively, a reflected power bridge or VSWR bridge may be used to drive both tune and load variables, but iteration is required.

2) Loading

Conductive, capacitive or inductive load means L can be used to match the source antenna 30 to the

impedance of the RF generator 31 and the connecting coaxial cable 31C. For example, a tap or wiper may be ohmically contacted to the antenna close to or at the 50 ohm or 300 ohm or other generator output impedance location along the antenna. Alternatively, a variable inductance or a variable capacitance may be connected to the generator output impedance point 50 on the antenna.

3). Tune and Load Circuits

Referring to FIGS. 4 to 9, preferably, tune means T is provided which is integral to the source antenna 30 to tune the source to resonance. Also, integral load means L is provided to match the input impedance of the source antenna 30 to the output impedance of the associated power generator 31 (or transmission line 31C). Referring to FIG. 4, in one aspect, the tune means T is a variable capacitance which is electrically connected between one end of the antenna 30 and RF ground.

As shown in FIG. 5, in another aspect the load means L may be a variable capacitance which is electrically connected between one end of the antenna and RF ground. Also, the load means may be a variable position tap 60 which applies RF input power to the antenna. See FIG. 6.

In a preferred combination shown in FIG. 7, the tune means T is a variable capacitance which is electrically connected between one end of the antenna 30 and RF ground and the load means L is another variable capacitance which is electrically connected between the other end of the antenna and RF ground. In this arrangement, the RF input power can be applied to the antenna via a tap, that is, by a tap 60 applied along the antenna or at either end thereof. See FIG. 8. Alternatively, the RF power input connection 66 can be positioned at substantially the connection between the load variable capacitance L and the end of the antenna 30, as shown in FIG. 9.

6. SOURCE BIAS PROCESS CONTROL

The invention also incorporates the discovery that the etch rate of materials such as silicon dioxide is increased and the etch selectivity of silicon dioxide relative to materials such as silicon is increased by using a sufficiently high bias voltage to provide a high silicon dioxide etch rate and periodically pulsing the bias voltage to a low value.

1) Pulse/Modulated Bias-Enhanced Etch Rate and selectivity

Referring to FIG. 10, typically the etch rates of materials such as silicon dioxide, SiO_2, increase with the bias voltage. Thus, increasing the bias voltage increases the etch rate of the oxide. Unfortunately, however, the etch rates of associated materials in the integrated circuit structure such as silicon/polysilicon also increase with the bias voltage. Thus, the use of a bias voltage of sufficient magnitude to provide a very high silicon dioxide etch rate also effects a silicon etch rate which (although somewhat lower than the oxide etch rate) is undesirably high and reduces selectivity. Quite obviously, when etching silicon dioxide it is highly desirable to have the high oxide etch rate characteristic of high DC bias voltages, V_h, combined with the relatively low silicon etch rate characteristic of low DC bias voltages, V_l, and, thus, high oxide selectivity.

Referring to DC bias voltage wave form 70 in FIG. 11, the seemingly contradictory goals expressed in the previous paragraph of combining the V_h and V_l characteristics are, in fact, achieved in polymer-forming etch processes (those processes which form an etchsuppressant polymer on materials such as silicon) by using a high base line DC bias voltage, V_h, and periodically pulsing or modulating the voltage to a low value, V_l. V_l is at or below the crossover point/voltage 68, FIG. 10, between silicon etching and silicon deposition, yet is at or above the oxide crossover point/voltage 69. As a result, a protective polymer is deposited on the silicon to suppress etching thereof during return to the high rate etch voltage, V_h, but no or insufficient deposition occurs on the oxide to significantly suppress the etching of the oxide at V_h. Preferably, V_l is characterized by deposition on the poly, but at least slight etching of the oxide. In a presently preferred embodiment, the values of the parameters; V_h (the high DC bias voltage), V_l (the low DC bias voltage), Pw (the pulse width of the low voltage, V_l), and P_{rp} (the pulse repetition rate or combined width of the low voltage and the high voltage pulses) are, respectively, -400 V, -225 V, about 0.1 seconds, and about 1 second.

2) Dual Frequency Bias

An alternative approach is depicted by DC bias voltage wave form 71 in FIG. 12. A relatively low frequency voltage variation is superimposed on the basic bias voltage frequency. For example, a slow